

# A study on the sharp knee and fine structures of cosmic ray spectra

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## ABSTRACT

The paper investigates the overall and detailed features of cosmic ray (CR) spectra in the knee region using the scenario of nuclei-photon interactions around the acceleration sources. Young supernova remnants can be the physical realities of such kind of CR acceleration sites. The results show that the model can well explain the following problems simultaneously with one set of source parameters: the knee of CR spectra and the sharpness of the knee, the detailed irregular structures of CR spectra, the so-called “component B” of Galactic CRs, and the electron/positron excesses reported by recent observations. The coherent explanation serves as evidence that at least a portion of CRs might be accelerated at the sources similar to young supernova remnants, and one set of source parameters indicates that this portion mainly comes from standard sources or from a single source.

*Subject headings:* cosmic rays – knee – fine structures –  $e^+e^-$  excesses – “component B” – single source

## 1. introduction

Since the discovery by Kulikov & Kristiansen (1958), the “knee” of cosmic ray spectra has been one fundamental problem of CR physics for half a century. Many theoretical works try to explain this interesting and important phenomenon. The most popular explanation attributes the knee to the inefficient acceleration of the Galactic CRs by the accelerators above PeV energies (e.g., Kobayakawa et al. 2002; Sveshnikova 2003; Erlykin & Wolfendale 2001). Alternative possibilities include the leakage of CRs when propagating in the Galaxy (Ptuskin et al. 1993; Roulet 2004; Lagutin et al. 2001), interactions between CRs and the background light (Karakula & Tkaczyk 1993; Candia et al. 2002) or neutrinos (Wigmans

2003) before arriving at the earth, or exotic interaction of CRs in the atmosphere where undetectable particles are produced and missing the detection (Nikolsky & Romachin 2000; Kazanas & Nicolaidis 2001).

From the experimental aspects, the measurements of the CR spectra around the knee region become increasingly precise, which can even reveal some fine structures of the knee. After a long term operation, the Tibet Air Shower array reported a very good measurement of the knee spectra with unprecedented high statistics and low systematics (Amenomori et al. 2008). Especially interesting signature of the Tibet result is that the CR spectra show a very sharp break of the spectrum index around 4 PeV. At almost the same time several experiments have reported their new measurements with the similar behavior, such as KASCADE(Apel et al. 2009), ARAGATS-GAMMA(Garyaka et al. 2008), Yakutsk(Ivanov et al. 2009), and MAKET-ANI(Chilingarian et al. 2007). Such a sharp knee challenges the traditional interpretations of the knee (Shibata 2009; Erlykin & Wolfendale 2009; Hu 2009). It is shown that if adopting an exponential-like cutoff of each component of CR species with low He flux, it will be very difficult to reproduce the sharp knee data (Shibata 2009). It is suggested by Hu (2009) that a double power-law may well fit the observational data with high He flux, which indicates that He may be the main component around the knee. Furthermore Hillas suggested that there should be another Galactic component, “component B”, to explain the CR spectra above 10 PeV (Hillas 2005).

Besides the sharp transition of the knee, Erlykin & Wolfendale (2009) carefully analyzed the CR spectra of individual experiment. By renormalizing the energy with respect to the break point(measured knee energy)of individual experiment, the problem related to the uncertainty of the absolute energy scale can be avoided, so the deviations of the observed spectra from the fitted spectra can be combined for all experiments. The result clearly shows the peculiarities at the positions expected for CNO group and Fe group if the knee is corresponding to the position of He. Interestingly the energies of these fine bumps are proportional to the mass number of the several major nuclei species: proton, He, CNO and Fe. The sharp knee and the irregularities of CR spectra are regarded as evidence for the single source origin of CRs (Erlykin & Wolfendale 2009).

Another important development in CR physics is the new discovery of electron/positron excesses by several experiments (Adriani et al. 2009; Chang et al. 2008; Aharonian et al. 2008, 2009; Abdo et al. 2009). To explain the positron fraction and electron spectrum excesses simultaneously one may need to introduce some exotic sources of  $e^+e^-$  pairs (Serpico 2009). Hu et al. (2009) (hereafter Paper I) proposed a model resorting to  $e^+e^-$  pair through interactions of CR nuclei and ambient photons around the acceleration sources, which can explain the knee of the CR spectra and the electron/positron excesses at the same time.

Based on that model we further study the detailed structures of the CR spectra in this work, intending to reproduce the sharp knee and fine structures mentioned above. In our interaction model the threshold energy of different chemical compositions is  $A$ -dependent, which will result in an  $A$ -dependent knee of each composition. This feature is consistent with the property of the fine structures found in experimental data (Erlykin & Wolfendale 2009). In addition, the interaction will cause a pile-up of the particles below the threshold. We expect this effect can contribute to the sharp knee and irregular bumps of the CR spectra.

This paper is organized as follows. In Sec. 2 we will first go over the model describing CR-photon interactions. In Sec. 3 we present the calculated results and comparisons with observational data of the sharp knee and irregular structures of CR spectra. Finally Sec. 4 is the conclusion.

## 2. Interactions between CRs and ambient photons

The model to explain the knee and electron/positron excesses using nuclei-photon interactions around the acceleration sources is proposed in Paper I. Here we readdress the basic physical picture and give some technical details.

There are three kinds of interactions between CRs and photons: pair production, photodisintegration and photo-pion productions processes when very high energy CR nuclei interact with background photons. The cross sections for pair production and photodisintegration are given in Blumenthal (1970) and Puget et al. (1976) respectively. The pion production cross section for proton is adopted from Particle Data Group et al. (2008), and we employ an  $A^{0.91}$  dependence for other nuclei with atomic number  $A$  (Stanev et al. 1985). The cross sections as functions of photon energy in the nuclei rest system for proton, He and Fe, which are the dominant compositions for CRs around the “knee” region (Hörandel 2003), are shown in the *left panel* of Fig. 1. Note that for proton there is no photodisintegration interaction. The pair production cross section is proportional to  $Z^2$  of the nuclei, so for heavy nuclei like Fe the pair production cross section is extremely large (Blumenthal 1970).

To see clearly the effects of the three interaction channels, we need to know the energy loss of the nuclei due to each of the interactions. The energy loss rate can be written as

$$\frac{dE}{dt} = \frac{\kappa E}{\tau(E)} = \kappa E \cdot \int d\cos\theta \frac{1 - \cos\theta}{2} \int d\epsilon n(\epsilon) \sigma(E, \epsilon, \cos\theta) c, \quad (1)$$

where  $\tau(E)$  is the average interaction time of the nuclei in a radiation field with number density  $n(\epsilon)$ ,  $\theta$  is the angle between photon and nuclei momenta,  $c$  is speed of light, and

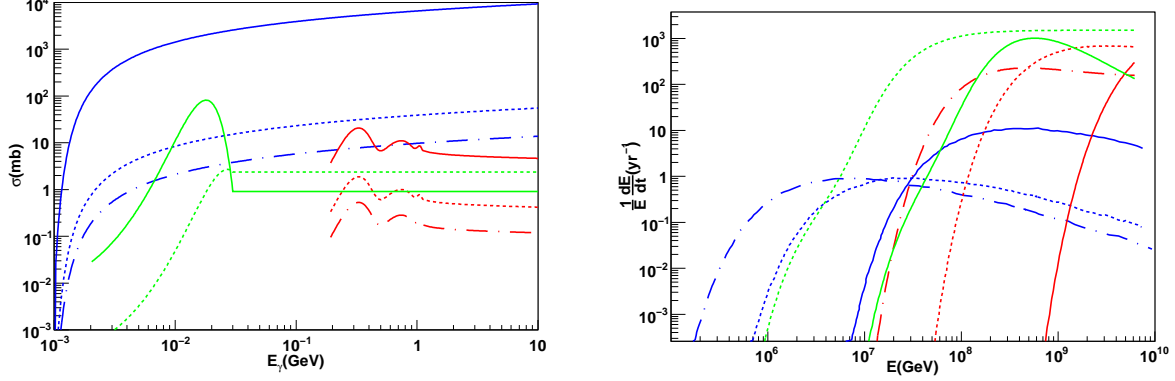


Fig. 1.— *Left*: cross sections as functions of photon energy in the nuclei rest system for proton (dash-dotted), He (dashed) and Fe (solid) respectively. For each kind of nuclei, the cross sections for the three interaction processes: pair production (blue), photodisintegration (green) and pion production (red) are shown. *Right*: the average relative energy loss rates  $\frac{1}{E} \frac{dE}{dt}$  for proton, He and Fe due to pair production, photodisintegration and pion production interactions in a 5000 K blackbody radiation field with respect to the nuclei energy in laboratory system. The labels of lines are same as in the left panel.

$\kappa$  is the average fraction of energy loss in one collision, i.e. the inelasticity. We plot in the *right panel* of Fig. 1 the average relative energy loss rates with respect to the nuclei energy in laboratory system due to each of the interactions for proton, Helium and Iron respectively. The background radiation field in the calculation is specified to be blackbody field with  $T = 5000$  K. The average inelasticity  $\kappa$  for pair production is calculated using a Monte-Carlo (MC) study to average the output  $e^+e^-$  pair energies for many realizations. For photodisintegration process the inelasticity is simply adopted as  $\kappa = i/A$  with  $A$  the total number of nucleus and  $i$  the number of nucleons kicked out in one interaction. It is shown that  $i = 1$  is dominant for photon energy below 30 MeV in the nuclei rest system (Puget et al. 1976). For pion production the average inelasticity is adopted as  $\kappa = \frac{1}{2} \left( 1 + \frac{m_\pi^2 - m_A^2}{s} \right)$  with  $m_\pi, m_A$  the masses of pion meson and nuclei, and  $s$  the center-of-moment system energy Stecker (1968). We can see from Fig. 1 that for energies lower than several PeV, the pair production dominates the energy losses for proton and Helium. The photodisintegration process of Helium become important above  $\sim 4$  PeV. Pion production is only important for energies higher than several tens PeV.

We use MC method to simulate the interactions between CR nuclei and ambient photons. The acceleration processes and interactions are decoupled for simplicity. The CR nuclei are assumed to inject into the radiation field with power-law spectra and proper

relative abundance according to the measurements (Hörandel 2003; Bertaina et al. 2008). Note here we adopt a correction of the measured spectra to the source spectra, taking into account the propagation effect (see below). After interactions the CRs together with the  $e^+e^-$  products enter the interstellar environment and propagate diffusively in the Galaxy. For the propagation of CR nuclei we simply use the leaky-box model with escape time  $\tau_{\text{esc}}(R) \approx 2 \times 10^8 \left(\frac{R}{\text{IGV}}\right)^{-0.6} \text{ yr}$  (Putze et al. 2009). The propagation of  $e^+e^-$  is a bit complicated since the dominant effect is energy loss due to synchrotron radiation and inverse-Compton scattering, instead of diffusion (or to say escape). We adopt GALPROP code to calculate the propagation of electrons and positrons.

The radiation field around the acceleration source is assumed to be of blackbody shape, with a temperature several to ten thousand Kelvin. It might be true for the young supernova shortly after its explosion. The intensity of the radiation field does not have to be as intense as the blackbody radiation. We keep the density of photons as a free parameter. The photon density multiplied with the interaction time gives the effective interaction probability.

As we have stated in Paper I, the photodisintegration of heavy nuclei, especially He, will overproduce protons through secondary production of protons. Therefore we do not expect the photodisintegration to play a significant role in the interaction process. We find that an evolving picture with decaying and asymptotically cooling of the radiation field can naturally explain this requirement. Schematically speaking the photodisintegration and pion production have higher threshold, which requires longer time for CR nuclei to be accelerated to exceed the threshold. But as time goes on the temperature of the radiation field may become lower and lower, and the interactions of photodisintegration and pion production need even higher energies of CRs. Therefore the photodisintegration and pion production can be effectively suppressed, and only the pair production takes effect.

### 3. Results

The calculated energy spectra of individual composition, including proton, He, CNO and Fe, together with the observational data are shown in Fig.2. The main parameters used in the MC calculation, including the relative abundances and spectral indices at the source, temperatures of radiation field, photon column density, and equivalent time for blackbody field, are compiled in Table 1. The relative abundances are adopted to reproduce the locally observed fluxes of each species. As same as in Paper I, only one set of parameters is enough to describe all spectra well. A few model parameters are slightly adjusted in order to better agree with the fine structures of CR spectra(see detailed explanation below). However, the basic features as shown in Paper I are kept unchanged. The power-law index and

normalization of each chemical composition are the same as that used in Paper I, except for CNO group we use a harder injection spectrum by 0.06 and a lower flux normalization at 1 TeV by 10% according to Bertaina et al. (2008), which will make the flux slightly go up around the knee region. The temperatures of the radiation field for proton and He, which are the main compositions of CRs, remain the same as in Paper I. However, we change the temperature for Fe from  $\sim 2000$  K in Paper I to  $\sim 3500$  K in this work. In Paper I we set a lower temperature for Fe with the purpose that the second knee around  $300 - 400$  PeV might be reproduced using the drop of Fe spectrum. If we relax this requirement we have shown that a wide range of the temperature for Fe can be consistent with the current data (see the systematic check done in Paper I). As we will see below, a higher temperature for Fe will be better to reproduce the fine structures of the total CR spectrum. For other nuclei which do not play a significant role, we use the temperature field 5500 K for  $3 \leq Z \leq 25$  and 3500 K for  $Z \geq 26$  respectively. It is shown that the model expectations are consistent with the observational data. However, since the current measurements of individual CR composition are actually not very good, the constraints on the model parameters are weak.

The case for the all-particle spectra is much better than the individual composition. The comparison of the all-particle spectra between our theoretical prediction and the data is shown in Fig.3 We can see the knee forms due to the break of He spectrum around  $\sim 4$  PeV. This condition would require the temperature of radiation field which He experiences is about 7000 K. The pile-up of He particles around the threshold point helps to better produce the sharp break of the knee spectrum. To investigate the break behavior more quantitatively, we adopt the following double power-law function to fit the CR spectrum below and above the knee (Erlykin & Wolfendale 2009)

$$I(E) = AE^\gamma \left[ 1 + \left( \frac{E}{E^k} \right)^\delta \right]^{-\frac{\Delta\gamma}{\delta}}, \quad (2)$$

where  $\gamma$  is the spectrum index below the knee, which changes by  $\Delta\gamma$  above the knee,  $\delta$  is

Table 1: Parameter settings in the Monte-Carlo calculation.

	relative abundance $10^5 \text{ GeV} - 10^9 \text{ GeV}$	$\gamma_z$	$T_{\text{ph}}$ (K)	$\langle n\tau \rangle$ ( $10^{29} \text{ cm}^{-2}$ )	$\hat{\tau}$ (yr)
Proton	1.00	2.14	$1.0 \times 10^4$	8.1	0.04
Helium	0.66	2.02	$7.0 \times 10^3$	12.9	0.19
CNO	0.30	2.02	$5.5 \times 10^3$	7.0	0.21
Iron	0.23	2.03	$3.5 \times 10^3$	2.0	0.23

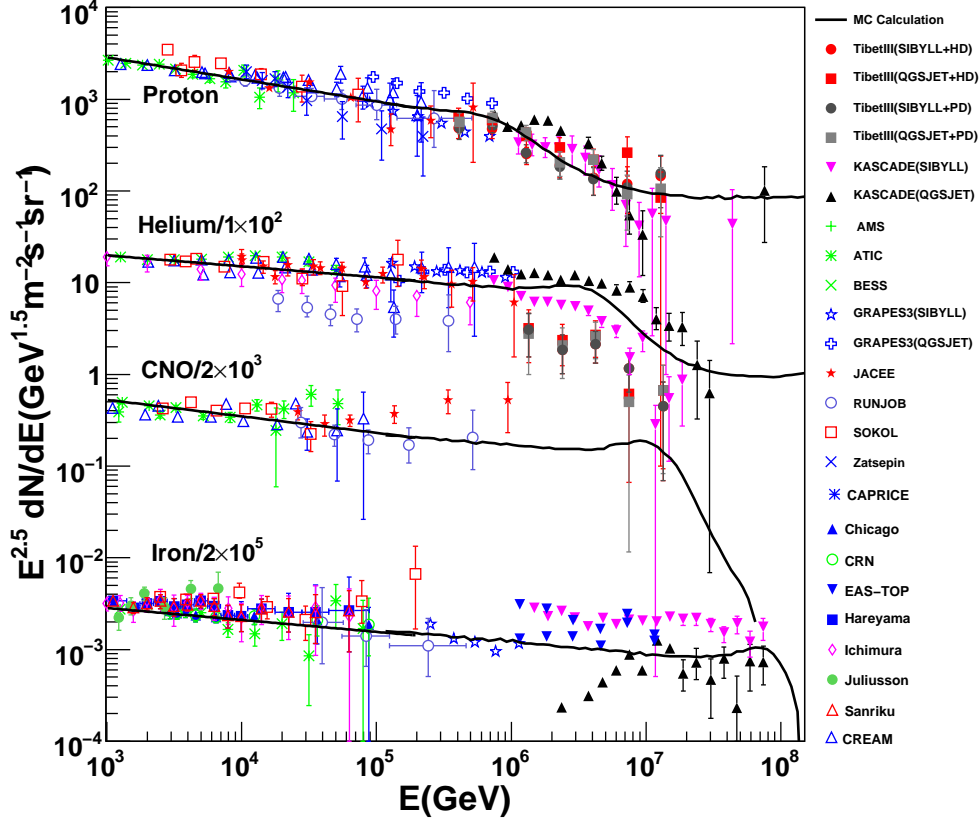


Fig. 2.— Energy spectra for proton, He, CNO and Fe. The solid lines are the MC calculated results. Observational data are Tibet-III (Amenomori et al. 2006), KASCADE (Antoni et al. 2005; Apel et al. 2009), AMS (Alcaraz et al. 2000; AMS Collaboration et al. 2002), ATIC-2 (Panov et al. 2009), BESS (Haino et al. 2004), GRAPES-3 (Gupta et al. 2008), JACEE (Asakimori et al. 1998), RUNJOB (Apanasenko et al. 2001), SOKOL (Ivanenko et al. 1993), Zatsepin (Zatsepin et al. 1993), CAPRICE (Boezio et al. 2003), Chicago (Mueller et al. 1991; Swordy et al. 1995), CRN (Mueller et al. 1991), EAS-TOP, Hareyama (Hareyama 1999), Ichimura (Ichimura et al. 1993), Juliusson (Juliusson 1974), Sanriku (Kamioka et al. 1997), CREAM (Yoon et al. 2008; Ahn et al. 2009);

the sharpness parameter which describes the smoothness of the transition. The sharpness  $S$  (the second-order derivative of spectrum at the energy break point  $E_k$ ) is defined as (Erlykin & Wolfendale 2009)

$$S = \delta \Delta \gamma \frac{\ln 10}{4}. \quad (3)$$



Through fitting the theoretical calculated spectrum we can obtain the sharpness  $S = 2.0$ , while the sharpness of experimental data of Tibet air shower array is about  $2.4 \pm 0.8$ , which shows good consistence with the theoretical one.

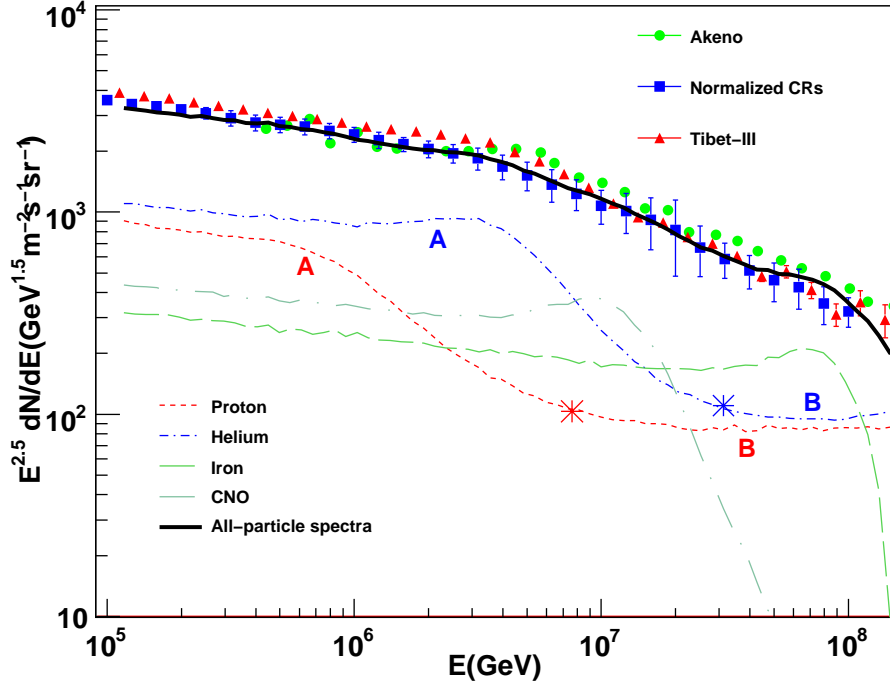


Fig. 3.— The calculated all-particle spectrum. Also shown are proton, He, CNO and Fe components. The observational data: Tibet-III(Amenomori et al. 2008), Akeno (Nagano et al. 1984). The *Normalized* data are derived by combing all data with a rescale based on the extrapolation of the direct measurements(Hörandel 2003). Label “B” indicates the high energy tails of the proton and He spectra above marker “\*” can be regarded as the “component B” of the Galactic CRs as suggested by Hillas (2005).

We can also note that there are high energy tails of the proton and He spectra due to the decrease of the pair production energy loss rate (Fig. 1). This behavior is very similar to the ankle of the ultra high energy CRs generated by  $e^+e^-$  pair production interactions with cosmic microwave background photons (Berezinsky et al. 2006). Coincidentally, it may be a natural explanation of the “component B” of the Galactic CRs as suggested by Hillas (2005) when studying the overall property of CR spectrum. However for the heavy nuclei, there are no obvious high energy tails due to large cross sections and the constant temperature of individual component, as shown in 1.

Fig. 4 shows a more detailed comparison between theory and data, after subtracting



the main behavior as fitted using Eq.(2), which enables us to explore the fine structures of the CR spectra. The data points are combined using 6 experiments, Tibet Air Shower array(Amenomori et al. 2008), KASKADE(Apel et al. 2009), ARAGATS-GAMMA(Garyaka et al. 2008), Yakutsk(Ivanov et al. 2009),MAKET-ANI(Chilingarian et al. 2007) and TUNKA [56] according to Erlykin & Wolfendale (2009). To avoid the uncertainty of energy calibration among various experiments, we fit the break energy  $E^k$  in Eq.(2) for each data set and then normalize it to the Tibet result. It is shown in Fig.2 that the fine structures of the theoretical calculation is well consistent with the observational data. The position  $\log(E/E^k) \sim 0.0$  corresponds to He, and the two bumps at  $\log(E/E^k) \sim 0.5$  and  $\log(E/E^k) \sim 1.3$  should correspond to CNO group and Fe respectively. The constraints on the model parameters are not very strong using the present observational data, e.g. the final results do not change significantly by varying the temperature parameters by several tens percent.

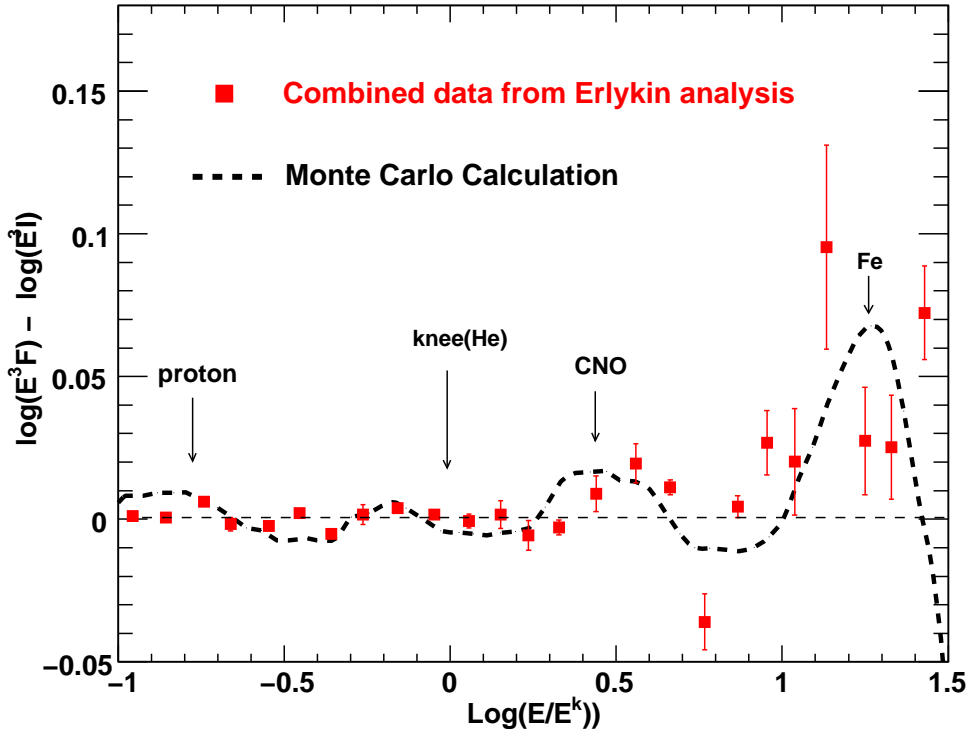


Fig. 4.— The fine structures of CR spectrum: theory versus data.  $F$  means the observational or calculated flux of the total CR spectra, while  $I$  indicates the fitting to  $F$  according to Eq. (2). The data are combined results of 6 experiments according to Erlykin & Wolfendale (2009). The positions  $\log(E/E^k) \sim -0.7$  and  $\log(E/E^k) \sim 0.0$  correspond to proton and He, and the two bumps at  $\log(E/E^k) \sim 0.5$  and  $\log(E/E^k) \sim 1.3$  correspond to CNO group and Fe respectively.

Finally we check the spectra of  $e^+e^-$  and position fraction of these new parameters and

find almost identical results as that derived in Paper I. This is reasonable because the basic parameters of proton and He, which produce the main part of the electrons/positrons, are almost unchanged.

#### 4. Conclusion

In summary we use the pair production interaction model between CR nuclei and ambient radiation field proposed in Paper I to explain the features of the CR spectra, including the sharp knee and fine structures. Results show that the spectra of CRs agree well with the observations. In our model, the He composition dominates around the knee at  $\sim 4$  PeV. The sharp knee observed by Tibet air shower array and confirmed by more and more experiments, can be well reproduced through the pile-up of He particles. In addition, this model can explain the fine structures of CR spectrum through the pile-up effects of CNO group and Fe nuclei. As an additional result, our model can provide a natural explanation of the “component B” problem of individual composition in tens of PeV energy range as suggested in Hillas (2005). As in Paper I, the electron/positron excesses can also be explained.

Furthermore we would like to discuss some implications of the model parameters. We note that only one single set of parameters is enough to explain the data. As discussed in Paper I and Hu (2009), it may indicate that the sources are “standard” which have similar parameters such as the temperature evolution of the radiation field, the relative abundances and spectral indices for individual elements, or the observed fine structures of CRs spectra are mainly due to one single source, either nearby or not so nearby but intensive (e.g. possibly the Galactic center). This work can be regarded as one progress approaching the origin of CRs.

We thank A. D. Erlykin, A. W. Wolfendale, Y. H. Tan, and L. K. Ding for helpful discussions and comments on the paper. Hong-Bo Hu thanks Wei Wang for long-term help with the research work. This work is supported by the Ministry of Science and Technology of China, Natural Sciences Foundation of China (Nos. 10725524 and 10773011), and by the Chinese Academy of Sciences (Nos. KJCX2-YW-N13, KJCX3-SYW-N2, GJHZ1004).

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